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ARCTIC OCEANOGRAPHY AND METEOROLOGY REVIEW

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This report presents an overview of Arctic oceanography and meteorology in addition to acoustic properties of the Arctic Ocean relevant to sonar system performance. Acoustic modeling techniques appropriate to ice-covered ocean areas are also discussed. Environmental-acoustic data are identified which can support sonar performance modeling efforts.

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SECTION I

INTRODUCTION

BACKGROUND

The 1984 Research and Policy Act mandated the development of a comprehensive 5-year Arctic Research Plan. The first phase in the preparation of this plan has been documented in a report entitled "National Needs and Arctic Research: A Framework for Action," published by the Arctic Research Commission in 1986.[1] Figure 1 is a schematic summary of national research issues and priorities.

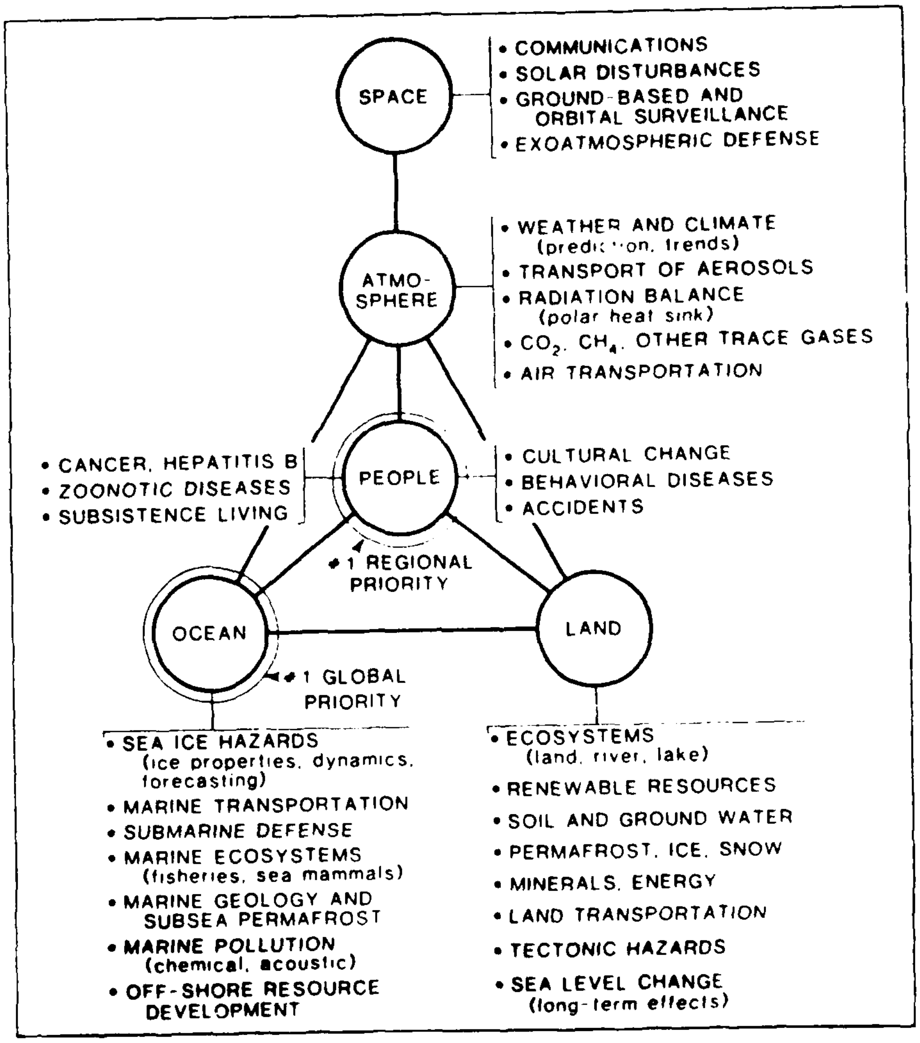

FIGURE 1: PRINCIPAL COMPONENTS OF THE ARCTIC SYSTEM AND RELATED NATIONAL ISSUES REQUIRING SCIENTIFIC AND ENGINEERING RESEARCH[1]

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1. J.G. Roederer, "Research Priorities in the Arctic: U.S. Arctic Research Commission Gets Down to Business," Transactions of the American Geophysical Union, Volume 67, Number 24, 1986, pp. 521-522.

The Arctic region has recently become a focal point of U.S. Naval interest owing to perceived utilization of this ocean area by Soviet strategic and tactical submarine forces.[2] Assessments of Anti-Submarine Warfare (ASW) and Undersea Warfare (USW) sensor system performance in the Arctic Ocean have correspondingly received a great deal of attention in attempts to establish baselines of operational effectiveness. The sometimes disquieting results of these assessments have further prompted evaluations of advanced sensor system concepts in the Arctic environment. However, such performance assessments are fraught with considerably more frustration than similar assessments in more temperate ocean areas due to an extreme sparsity of Arctic environmental-acoustic data. The limited data which are available, particularly for ice-covered areas, tend to be biased toward spring since this season provides the most hospitable weather for ice camps.

OBJECTIVES

The objectives of this report are:

1) identify key components for modeling Arctic acoustics
2) estimate effects of ice-cover
3) evaluate frequency dependence of ice-cover effects
4) specify existing models and their applicable range of operation
5) identify noise characteristics and methods of noise generation
6) review literature.

In order to accomplish these objectives, this report addresses four major topics: Arctic Oceanography (Section II); Arctic Acoustic Environment (Section III); Arctic Acoustic Models (Section IV); and Arctic Acoustic Data (Section V).

2. Mobile Sonar Technology (MOST), 1983.

SECTION II

ARCTIC OCEANOGRAPHY

GEOMORPHOLOGY

The Arctic Ocean is the fourth largest of the world's oceans, covering an area of approximately 13 x 10^6 km^2. The Arctic Ocean is considered to be a mediterranean sea since it is surrounded by a continental shelf which is interrupted only by the deep passage between Greenland and Spitsbergen called the Fram Strait.[3,4] These shelf areas and peripheral land boundaries form six marginal seas: Barents, Kara, Laptev, East Siberian, Chukchi, and Beaufort. Table 1 summarizes pertinent features of the first four of these seas which have particular strategic importance due to the operation of Soviet submarines. The shelf from Greenland to Barrow is approximately 100 km wide while the shelf widths in the Chukchi, East Siberian, Laptev and Kara Seas are more typically 800 km. A number of submarine canyons indent the continental shelves, the largest of which is the Svataya Anna Canyon in the northern Kara Sea which spans over 500 km.

The Arctic Ocean proper is divided into the Eurasian and Amerasian Basins by the Lomonosov Ridge. These two basins are in turn divided by secondary ridges: the Eurasian Basin by the Nansen Ridge (an apparent extension of the mid-Atlantic Ridge) and the Amerasian Basin by the Alpha Ridge (Figure 2); both of these secondary ridges parallel the Lomonosov Ridge. The greatest depth of the Amerasian Basin is 4000 m while the deepest part of the Eurasian Basin is 5100 m.

CONTINENTAL MARGINS. The widest margin is located in the Arctic and is known as the Barents Sea Shelf with shelf width extending out to approximately 90 km. The Arctic shelves break at great depths. This shelf depth along the outer margins lie at 350-400 m and only near the Chukchi Sea, East Siberian and Mackenzie delta is the depth of the shelf break close to that of the normal open ocean of 200 m. Sediments from the Canada Basin appear to approach from the direction of the Canadian islands. Sediments passing through the Barrow Canyon appear to be produced as erosional material flowing from the Bering Strait. The sediments on the floor of the East Siberian Sea is marked by relict drainage patterns from sedimentary material (river depositional) carried in the past presumably by the ancient Indigirka and Kolyma Rivers. The Laptev Sea appears to be associated with sedimentary type material related to erosion, deposition and tectonic processes. The Barents Sea Shelf region appears to be associated with tectonic movements and therefore tectonically related types of irregular sedimentary material. The Barents and Kara Seas appear to have shelf breaks at around 400-500 meters.

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3. SCOR (Scientific Committee on Oceanic Research) Working Group 58, "The Arctic Ocean Heat Budget," University of Bergen (Norway) Geophysical Institute Report No. 52, 1979.

4. Applied Physics Laboratory, "A Perspective of Submarine Arctic Operations," Johns Hopkins University, 1982.

TABLE 1: SUMMARY OF GEOMORPHOLOGIC DESCRIPTIONS OF SELECTED ARCTIC CONTINENTAL SEAS

DESCRIPTOR \ AREA	BARENTS SEA	KARA SEA	LAPTEV SEA	EAST SIBERIAN SEA
AREA	130×10^4 km^2	88.3×10^4 km^2	54×10^4 km^2	66×10^4 km^2
DEPTH	typically 100 - 350 m	average depth 118 m	64% of depths less than 100 m	typically 10 - 40 m
BOTTOM COMPOSITION	sand, mud	silt clay, mud, terrigenous silt of glacial marine type	sand, mud, pebbles, broken boulders	sandy silt, fractured boulders and pebbles (ice-transported)
EXTENT OF ICE COVER	southern part does not freeze; ice floe boundary is 400 - 500 km from shore	ice-covered most of year; central ice not solid or continuous	ice-covered most of year	ice-covered most of year

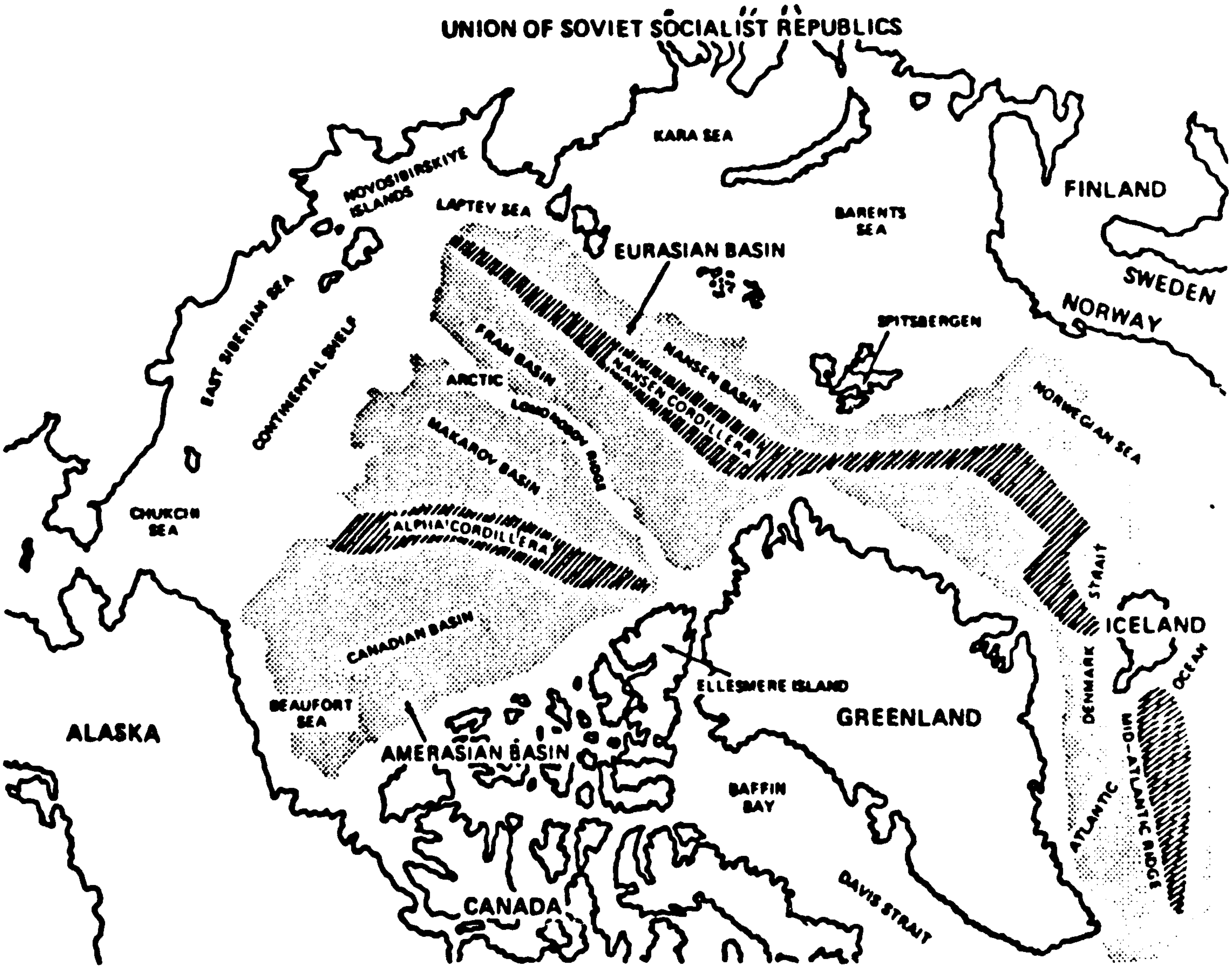

FIGURE 2: GEOMORPHOLOGY OF THE ARCTIC OCEAN BASIN[5]

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5. ibid.

ABYSSAL FLOOR. The most extensive Arctic abyssal plain is found in the Canada Basin covering approximately 254,000 km^2 at approximately 3,800 meters of water depth. Depth variations in the Canada Basin increase from east to west indicating most likely that the source of sedimentary material for this basin approaches from the Canada Shelf. The Makarov Basin appears to receive sedimentary material from the East Siberian Sea.

SEDIMENTOLOGY. The sedimentology of the Eurasia shelf and the central portions of the Arctic Basin is extremely variable. In general, the continental shelves of the Arctic Basin are covered with a thin layer of unconsolidated sand, mud and gravel. The deep Arctic Ocean floor appears to be covered with unconsolidated sediments. Influenced by ice debris, sorting of sediments on the shelf is assumed generally to be poor. Thickness of the shelf sediments which are underlain by Quarternary and Paleozoic sediments is assumed to be approximately 18 km. Unconsolidated sediments of the Chukchi Sea are assumed to be approximately 4 to 12 meters in thickness for the most part. Not surprisingly, the sediments near the Bering Sea shelf region are minimal. This appears to be due to the known swift subsurface inflow currents entering the Arctic Ocean through the Bering Strait. Further north, however, near 72°N, 160°W, sediment thicknesses reach 30 m. Although a sediment layer exists over the Chukchi Rise, the sediments are assumed to be unconsolidated and poorly covering the basement rock. Much of the Chukchi Sea and portions of the East Siberian and Laptev Seas are assumed to possess sediment thicknesses of between 3 to 8 km. Crystalline rocks on the ocean floor and sediment thicknesses to 500 meter in some parts are assumed for the Kara Sea. South of the Kara Sea, sedimentary thickness is presumed greater than 3,200 m but less than 4,100 m. The Barents Sea is described as having a crystalline basement complex with thickness of unconsolidated sediments to 20 km. Large amounts of turbidites and unconsolidated sediments can be assumed for all the floors of the abyssal plains of the Arctic.

WATER MASSES

The water masses of the Arctic Ocean can be described according to three types: 1) surface water, 2) Atlantic water, and 3) bottom water.[6,7] Each of these water masses will be discussed below.

SURFACE WATER (SW). The surface water (SW), which occupies the upper 200 m of the Arctic Ocean, is characterized by significant density stratification owing to a positive salinity gradient (salinity increases with depth).

The top 30-50 m of the SW is characterized by seasonal variations. In the winter, this layer is well mixed; in summer, a pronounced salt stratification is produced by ice melting.

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6. SCOR Working Group 58.

7. L.K. Coachman and K. Aagaard, "Physical Oceanography of Arctic and Subarctic Seas," In Marine Geology and Oceanography of the Arctic Seas, Y. Herman (editor), Springer-Verlag, 1974, pp. 1-72.

Below depths of 50 m, the SW characteristics differ according to basin. In the Eurasian Basin, salinity increases with depth while temperature increases with depth below a minimum, which typically occurs at about 75 m. In the Amerasian Basin, salinity increases less rapidly with depth; the temperature exhibits a relative maximum between depths of 50-100 m, followed by a minimum at about 150 m with a general increase with depth thereafter.

ATLANTIC WATER (AW). Relatively warmer, more saline Atlantic Water (AW) lies below the SW. As the name implies, this water originates in the North Atlantic Ocean and enters the Arctic Ocean through the Fram Strait. The AW is identifiable over the entire Arctic Basin by a temperature maximum at depths between 300 and 500 m.

BOTTOM WATER (BW). Beneath the AW lies relatively cold Bottom Water (BW). Within the Arctic Ocean, the BW is nearly isothermal within each of the two basins. However, below 1400-1500 m, a sharp temperature difference is evident across the Lomonosov Ridge (Figure 3). This depth probably represents the effective sill depth for the ridge, below which free exchange of water is prevented.

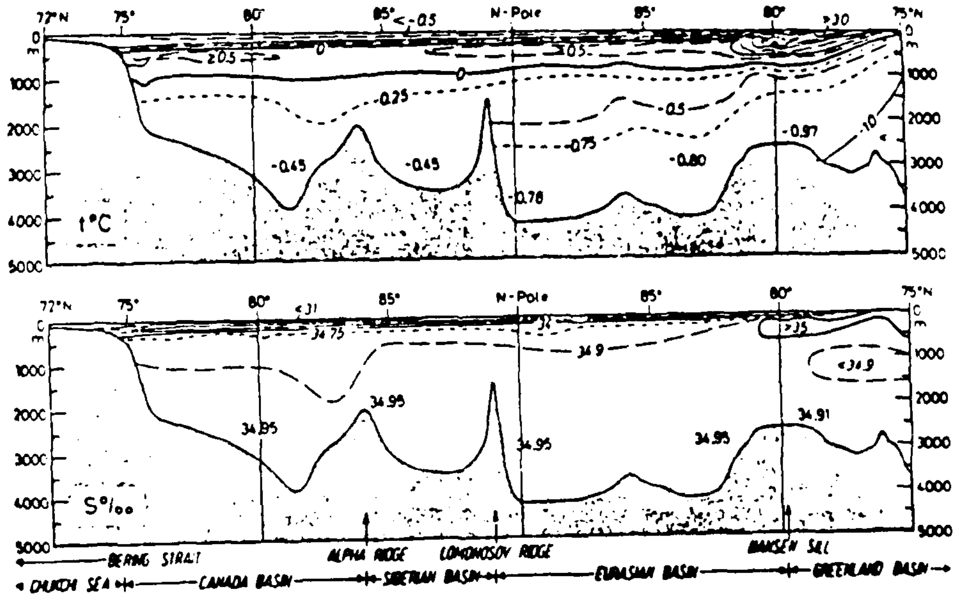

FIGURE 3: LONGITUDINAL SECTION OF TEMPERATURE AND SALINITY ACROSS THE ARCTIC OCEAN[8]

8. Coachman and Aagaard.

WATER CIRCULATION

The water circulation in the Arctic Ocean is best described by water mass.[9-11]

Currents in the Surface Water are slow (~ 10 cm s^{-1}) and are similar to observed ice motions, as discussed later. The Transpolar Drift Stream is directed from north of the Laptev and East Siberian Seas across the length of the Eurasian Basin, and exits through the western Fram Strait as the East Greenland Current. In the Amerasian Basin, the mean currents form a large anticyclone (clockwise) gyre. The general circulation of the upper waters is probably driven in large part by the prevailing wind patterns (Figure 4).

The general circulation pattern of the Atlantic Water appears to be counter to that of the Surface Water, at speeds generally below 5 cm s^{-1} (Figure 5).

The circulation of the Bottom Water is similar to that of the Atlantic Water.

ICE CHARACTERISTICS

Seventy percent of the Arctic Ocean is permanently covered with ice (Figure 6). Ice coverage is usually greatest in May and least in September. Except for the seas south of Spitsbergen, all waters north of the Arctic Circle are ice covered in winter; during summer, a large fraction of the waters south of 75°N are ice free for at least a few months out of the year. The Marginal Ice Zone, or MIZ, is a transition zone between open-water and ice-covered regions.[12,13]

CLASSIFICATION OF SEA ICE. Sea ice can generally be classified according to age, as described below.

> Young ice, as the name implies, is newly formed, perhaps only few hours to a few weeks old, with a thickness of less than 4 inches. Because brine is trapped in a network of small cells formed during freezing, young ice is generally very weak.

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9. Coachman and Aagaard.

10. A.J. Semtner, Jr., "Numerical Simulation of the Arctic Ocean Circulation," Journal of Physical Oceanography, Volume 6, 1976, pp. 409-425.

11. A.F. Treshnikov and G.I. Baranov, Water Circulation in the Arctic Basin, Gidrometeoizdat, Leningrad, 1972.

12. SCOR Working Group 58.

13. Coachman and Aagaard.

FIGURE 4: OBSERVED SURFACE CIRCULATION, DYNAMIC TOPOGRAPHY, AND LONG-TERM MEAN STATION DRIFTS[14]

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14. Coachman and Aagaard.

FIGURE 5: CIRCULATION OF ATLANTIC WATER IN THE ARCTIC OCEAN[15]

15. Coachman and Aagaard.

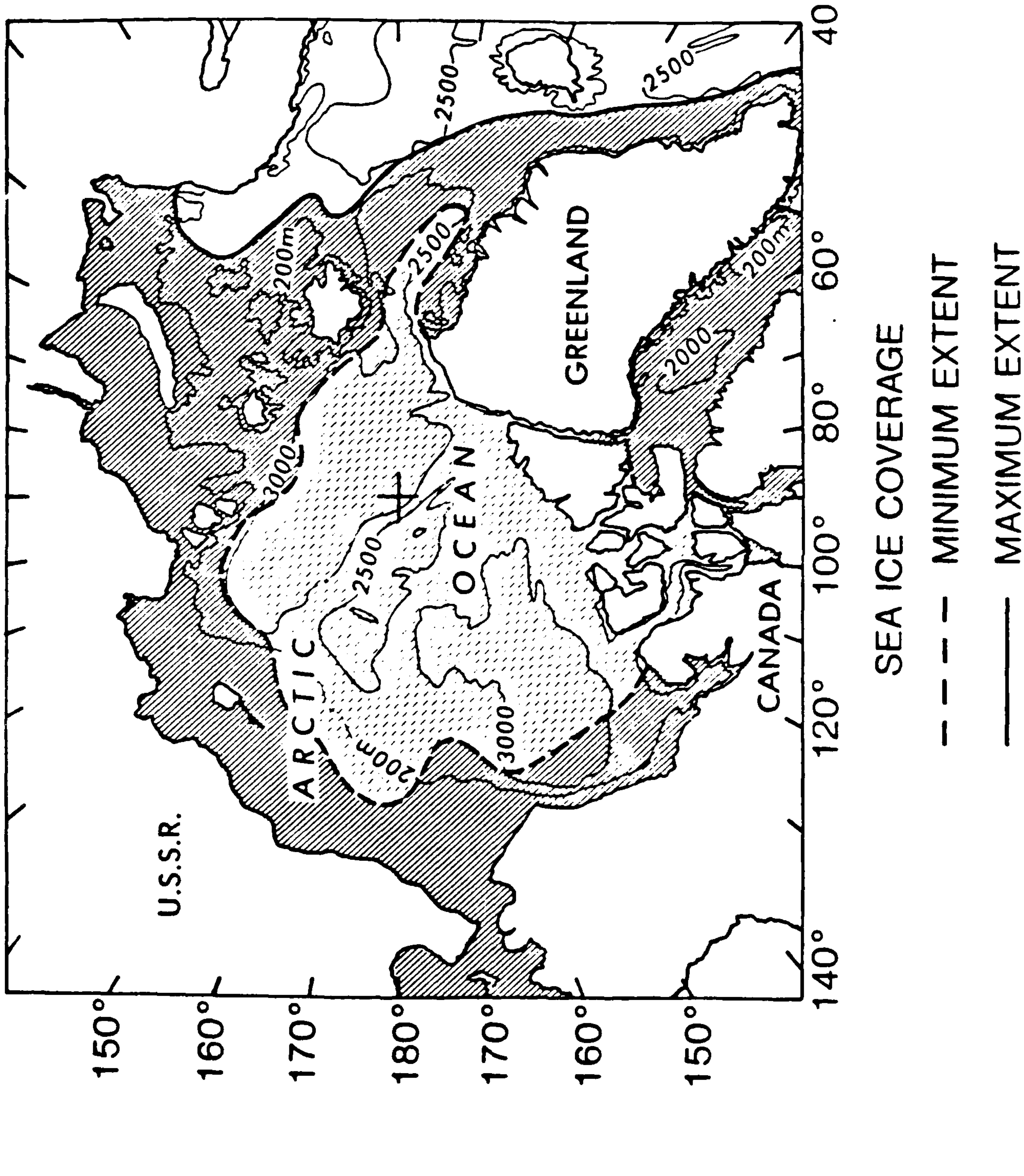

FIGURE 6: MINIMUM AND MAXIMUM EXTENT OF THE ARCTIC ICE COVER

First-year ice is ice of less than one year's growth and is usually less than 10 feet thick. During the first summer's melt season, surface water percolates through the ice, draining the trapped brine into the sea. Since brine volume is the principal parameter governing the strength of sea ice (inversely), first-year ice that survives the thaw becomes considerably stronger.

Multiyear ice has survived at least two melt seasons. Its thickness is determined by a balance between winter growth along its bottom surface and the summer melt from its top surface; it is rarely greater than 15 feet thick. Old ice can be very strong, indeed, especially at low temperature.

ICE MOTION.[16,17] Forces imposed by currents, wind, and the Coriolis effect cause the ice cover to move and to deform as floes converge and diverge. The drift of pack ice is controlled mainly by the latter two, the combination of wind stress and Coriolis force resulting in a movement to the right of the wind direction. A good rule of thumb is that pack ice drifts at a speed one-fiftieth of the wind speed.

The ice in the Amerasian Basin circulates clockwise in lock with the gyral pattern, and it may move as much as 10 miles a day, although a daily travel of 2 to 3 miles is more typical. Ice floes can orbit in this region for twenty years or more, but eventually they are shed into the Transpolar Drift Stream and carried out of the Arctic by the East Greenland Current. The Transpolar Drift Stream also transports ice from the Siberian shelf to the northeast of Greenland. The trip takes about five years (Figure 7).

Areas of open water, associated with leads or polynyas, usually refreeze quite rapidly, forming a web of thin ice between ice floes. When the floes later converge, this young and relatively weak ice is crushed and compacted into ridges or hummocks. The deformations can project above the surface as much as 40 feet and may extend below sea level more than 150 feet. Approximately 20% of the ice surface in the Arctic is covered by large ridges and hummocks, most of which are 10 to 15 feet high. Ridges composed of multiyear ice are the greatest obstacles to ship operations in the Arctic area.

About 12,000 icebergs are calved from the glaciers on the west coast of Greenland each year. A typical newly shed iceberg rises 260 feet out of the water from a base 1200 feet below the surface and displaces 1½ million tons. By the time it reaches the Atlantic, its displacement has been reduced to something on the order of 150,000 tons. At this stage, most icebergs are perhaps 50 feet high, with a ratio of above-to-below-water volume of roughly 1:7. Their drift is determined mainly by currents; an average of 400 annually reach North Atlantic waters where they are tracked by the International Ice Patrol. The number encountered during any given year is highly variable, however. Only a single iceberg was reported in 1958. The following year, the number sighted was more than 700.

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16. Applied Physics Laboratory, Johns Hopkins University.

17. W.D. Hibler, III, "A Dynamic Thermodynamic Sea Ice Model," Journal of Physical Oceanography, Volume 9, 1979, pp. 815-846.

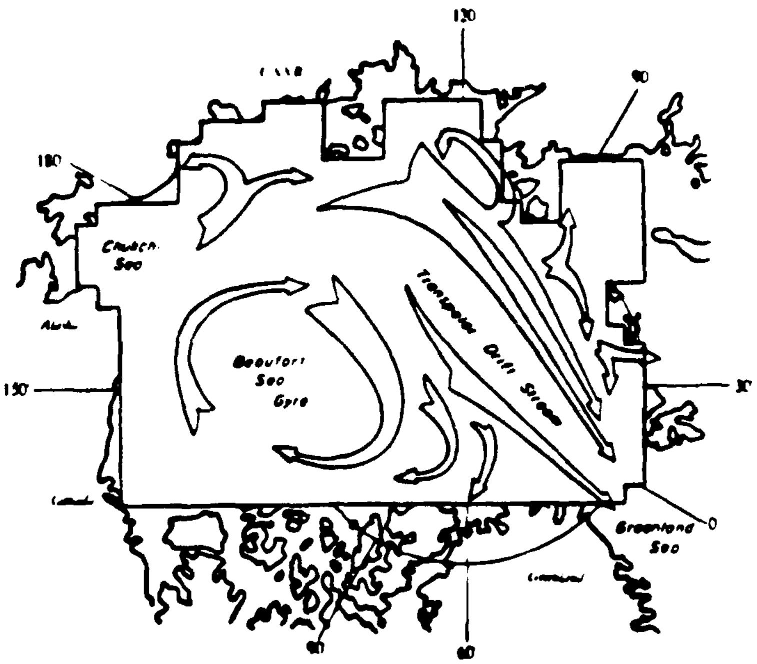

FIGURE 7: PATTERN OF MEAN ICE DRIFT IN THE ARCTIC OCEAN[18]

Ice islands have dimensions of several miles on a side and are 80 to 200 feet thick. They are almost never found in the Eurasian Basin. The usual drift pattern resembles a jagged circle; the islands orbit clockwise around the Amerasian Basin at an average rate of several miles per day.

BIOLOGICS

Biologic activity in the Arctic is of concern acoustically in two regards; 1) as a contributor to ambient noise, and 2) as a source of scatterers, or false targets. However, these aspects are considered minor in relation to the corresponding noise levels and scattering surfaces associated with sea ice[19] (refer to Section III for related discussions).

Sources of biologic noise in the Arctic region stem primarily from indigenous marine mammals. The Arctic Convergence - the mixing of cold low salinity water melting from the ice caps with the warm higher salinity water from the tropics along interfaces of oceanic current cells - creates relatively high productivity for the pelagic waters surrounding the polar ice packs. Although the Arctic waters contain roughly 1/4 of the nutrient levels of the Antarctic waters, populations of dinoflagellates, nannoplankton, and Euphasea (krill) are extensive and dense enough, particularly during spring blooms to be detected by satellites in space. As far as underwater sound production is concerned in the Arctic

18. Hibler.

19. Mobile Sonar Technology.

waters, the above populations along with mytilidae (mussels), Balanidae (barnacles), amphipod crustaceans, and fish (such as the Arctic cod) are important primarily for their attraction of marine mammals.[20] Mytilidae and Balanidae, in particular, produce isolated sound in warmer waters, but it is unlikely any noise of consequence is produced in the Arctic's cold waters.

Mammals attracted to the Arctic which are of importance to marine bioacoustics include walrus, seals, dolphins, and whales. The walrus bark seems isolated to the ocean surface and the dolphin and porpoise populations cluster towards the warmer or more shallow waters. Therefore, this section will deal only with seals and whales.

Studies indicate that seals and whales emit either codas, 3 to 40 clicks or more of 1/2 to 1 1/2 second duration in all, repeated 2 to 60 times or they emit song sequences of 20 minutes or more.[21] Seals predominately produce discrete frequencies and Erignathus barbatus (bearded seal) produces long (2 min. or more) repetitive song sequences. Furthermore, all singing whales in a given area produce the same song.

Mysticete whales produce low frequency 'moans and screams' from 20 cps in Physeter (sperm whale) to 1000 cps in B. megaptera (hump back). B. physalus (fin whale) and Physeter produce similar codas at 20 Hz under the following conditions:

- Upon approach of other whale(s)
- As an alert response asking for silence
- In response to unusual sounds as underwater landslides or the starting and stopping of ships engines.

Odontocete whales generally produce broad band clicks, sometimes narrow band squeals.[22] The rapid clicks at a rate of 400 to 500 per second may last one second or appreciably more with frequencies of a narrower band or of sudden frequency shifts not uncommonly in harmonics.

As a note, it should be remembered that the Arctic Convergence creates favorable conditions for the food sources that attract vocal marine mammals. Any great distance under solid ice, the Arctic seas become veritable deserts devoid of bioacoustic sources. Also, total whale densities are variable since migratory species congregate in northerly waters during the June-to-September

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20. Personal communication, Dr. Daryl Boness, National Zoo, Smithsonian Institution (Washington, DC).

21. W.A. Watkins and W.E. Schevill, "Sperm Whale Codas," Journal of the Acoustical Society of America, Volume 62, Number 6, 1977, pp. 1485-1490.

22. W.N. Tavolga (editor), Marine Bio-Acoustics, Proceedings of a Symposium held at the Lerner Marine Laboratory (Bimini, Bahamas, April 11 to 13, 1963), Pergamon Press, The MacMilan Company, New York, 1964, 413 pp.

feeding season and migrate south during the mating season; consequently, certain sound sequences such as the 20 cps phenomena occurring at roughly 16 sec. intervals attributable to B. physalus, a migratory species, most probably is absent during the winter months. Table 2 summarizes known bioacoustic sources in northern waters.

CLIMATE

The Arctic Circle (66° 33°N) is defined as the line of latitude at which the sun does not set on the day of the summer solstice (about June 21) and does not rise on the day of the winter solstice (about December 22)[23] (Figure 8).

Geologists and climatologists commonly delineate the Arctic region by the July 10°C isotherm (surface atmospheric temperature) which, over land, generally corresponds to the northern limit of tree growth (Figure 9).

The Arctic climatic year is divided into two seasons: a long, cold winter and a short, cool summer. Winter conditions over the Arctic Ocean are usually cold (-30°C to -35°C) and stable with clear skies. Summer conditions are characterized by a succession of weak cyclones; weather is typically damp and frequently foggy. The annual precipitation of 10-15 cm (similar to desert-region rainfall) is largely associated with the late summer cyclones.[24]

Interactions among the elements of air, sea and ice assume greatest importance in the MIZ. Moreover, it is in the MIZ that all facets of naval operations (air, surface, subsurface) share common concerns with regard to Arctic navigation and Arctic sonar performance.

Oceanographic conditions in the MIZ are dominated by permanent as well as transient frontal systems, by eddies, and by upwelling events along the ice edge. Exchanges of heat and momentum between sea and air are greatly affected by the presence of a broken ice cover. These phenomena play a major role in determining the thermal structure, and thus the sound speed structure, in the upper layers of the ocean. Further discussions concerning the acoustic characteristics of Arctic waters are presented in Section III.

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23. R.E. Huschke (editor), Glossary of Meteorology, American Meteorological Society, 1959, 638 pp.

24. Central Intelligence Agency, Polar Regions Atlas, GPO Stock No. 041-015-00094-2, 1978.

TABLE 2: SUMMARY OF BIOACOUSTIC SOURCES IN NORTHERN WATERS

Common Name	Genetic Name	Northernmost Range	Migratory
Beluga	Delphinapterus leucas	Shallow waters	No
Narwhal	Monodon monoceros	Pelagic in pack ice	No
Fin Whale	Balaenoptera physalus	Pelagic	Yes
Minke Whale	Balaenoptera acutorostrata	Pelagic to ice edge	Some
Blue Whale	Balaenoptera musculus	Pelagic to offshore	Yes
Bowhead Whale	Balaena nupticetus	Pelagic to Alaskan pack ice	No
Humpback Whale	Megaptera novaeangliae	Pelagic	Yes
Sperm Whale	Physeter macrocephalus	Pelagic to ice edge	
Gray Whale	Eschrichtius robustus	Near shore	Yes
Killer Whale	Orcinus Orca	Shallow and pelagic cool waters	
Northern Bottlenose Whale	Hyperoodan ampullatus	Deep water of deep Arctic	No
Harbor Porpoise	Phocoena phocoena	Shallow waters	No
White Beaked Dolphin	Lagenorhynchus albirostris	To northern ice	No
Walrus	Odobenus rosmarus	Shallow waters	Yes

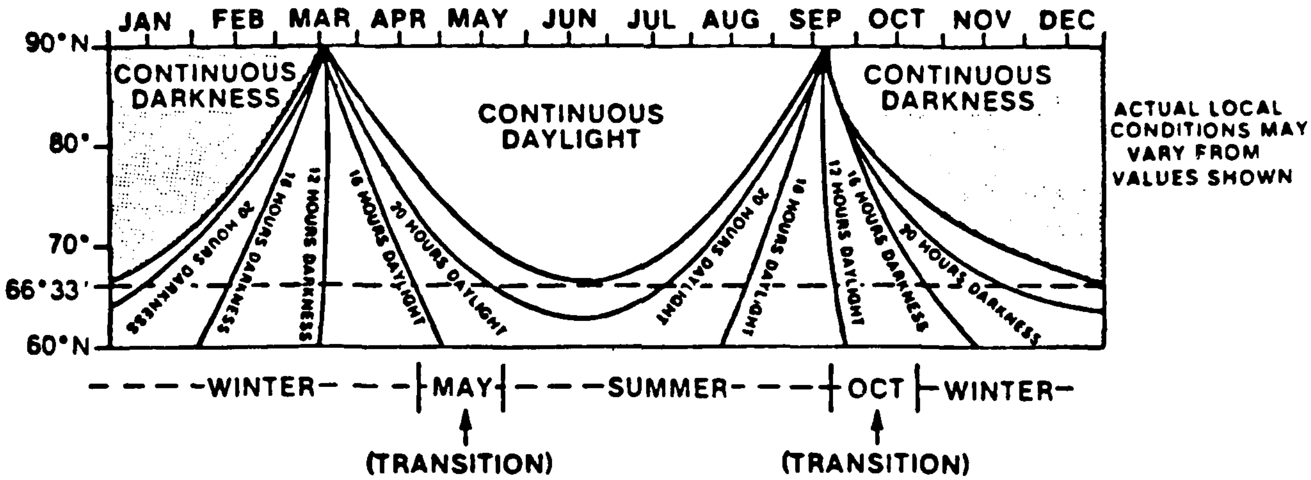

FIGURE 8: DURATION OF DAYLIGHT AT THE ARCTIC CIRCLE[25,26]

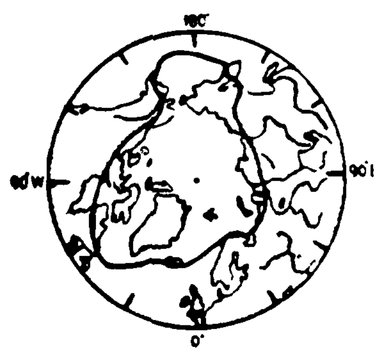

FIGURE 9: THE JULY 10°C ISOTHERM

25. Central Intelligence Agency.

26. J.P. Welsh, C.J. Radl, R.D. Ketchum, Jr., A.W. Lohanik, L.D. Farmer, D.T. Eppler and R.E. Burge, "A Compendium of Arctic Environmental Information," Naval Ocean R&D Activity Technical Note 290, 1984, 199 pp.

SECTION III

ARCTIC ACOUSTIC ENVIRONMENT

The Arctic acoustic environment is defined to include both the ice-covered oceans and the MIZ. This area has several distinctive characteristics which affect acoustic systems:

- a positive sound speed profile which produces a continuously upward-refracting propagation condition
- an ice cover, with rough undersurface features, which creates a unique acoustic scattering problem, and
- a noise environment dominated by ice-generated noise, with few commercial noise sources.

Furthermore, the Arctic environment can be segregated into three distinct regions according to the type of ice cover: 1) pack ice, 2) Marginal Ice Zone (MIZ), and 3) open ocean. The differing geometrical configurations associated with the degree of ice cover (and depth of water) afford substantially different environmental acoustic impacts on USW system operation and performance. Table 3 summarizes these impacts.

SOUND SPEED

The sound speed profile generally assumes one of two basic forms in pack ice Arctic waters: 1) positive gradient half-duct, and 2) multiple ducts arising when a positive gradient half-duct overlies a deeper refractive duct.[27] There is an additional seasonal dependence, arising from ice melting which causes the formation of brine pockets encased in relatively salt-free ice, which may result in poorer propagation conditions. The variability of profile type in the MIZ is significantly greater and this effect is particularly important. Figure 10 presents a typical sound speed profile for the Amerasian Basin. Figure 11 compares sound speed profiles from the Arctic and adjacent seas.

BOUNDARY INTERACTIONS

Due to the upward-refracting nature of acoustic propagation in the Arctic Ocean, surface reflection losses become increasingly important while bottom losses assume a less important role. The resulting multiple surface reflections play a dominant role in causing the Arctic Ocean to act as a low-pass filter.

SURFACE AND UNDERICE.[28] Field measurements have shown that forward scatter from a rough anisotropic ice canopy is a function of acoustic frequency, geometry, and the statistical (spatial correlation) properties of the ice canopy.

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27. This behavior derives from the differences in watermass structure between the Eurasian and Amerasian Basin, as discussed in Section II.

28. Mobile Sonar Technology.

TABLE 3: SUMMARY OF ARCTIC IMPACT ON ACOUSTIC CHARACTERISTICS[29]

PROPERTY	CONVENTIONAL	ARCTIC	IMPACT OF ARCTIC
SOUND VELOCITY PROFILE	VARIABLE WITH DEPTH AND TIME	VERY STABLE, UPWARD REFRACTING	RSR IS PRIMARY PATH - NO DEEP CHANNEL - $\frac{1}{2}$ CZ
NOISE	DRIVEN BY SHIPPING AND WIND	VARIABLE OVER AREA TRANSIENTS AND WIND LOWER UNDER PACK ICE HIGHER IN MIZ	NOISE CONTINUUM IS TRANSITORY IN NATURE. DIRECTIONAL. DI AND SIGNAL PROCESSOR OPERATIONAL PROBLEMS
TRANSMISSION LOSS	SPREAD LOSS AND ABSORPTION	SCATTERING, ABSORPTION SPREAD LOSS	MUCH HIGHER LOSSES - TRANSMISSION FILTER IS HIGHLY FREQUENCY DEPENDENT
SCATTERING - COHERENCY FACTORS	MINOR DIRECT PATH AND SURFACE REFLECTION IMPACT - BOTTOM MAY HAVE LARGE IMPACT	VERY ROUGH ICE AND MIZ CAUSE LARGE SCATTER LOSSES AND BOTH TIME, FREQUENCY AND SPATIAL SPREADS	INCREASES TRANSMISSION LOSS WAVEFORM DISTORTION, SIGNAL DISPERSION, SPATIAL PROCESSING DISTORTION
REVERBERATION	VARIABLE - DEPENDS UPON SCENARIO AND SCATTERER - VOLUME SURFACE AND BOTTOM	MUCH HIGHER LEVEL; LARGER DURATION, SURFACE BACKSCATTER; COHERENT ELEMENTS	AT SHORT RANGES, STRONG INTERFERENCE. MUCH HIGHER FALSE TARGET RATE. SIMILAR EFFECTS AT MID AND HIGH FREQUENCIES
ECHO STRUCTURE	MAY HAVE MULTIPATH AND FREQUENCY DISPERSION	SHORT RANGES ARE SIMILAR TO CONVENTIONAL; LONGER RANGES HAVE MORE SPREAD AND MULTIPATH	ECHO DEGRADATION (WAVEFORM AND ENVELOPE) DUE TO TIME AND FREQUENCY DISPERSION AND GROSS MULTIPATH

29. Derived from information kindly provided by SAIC.

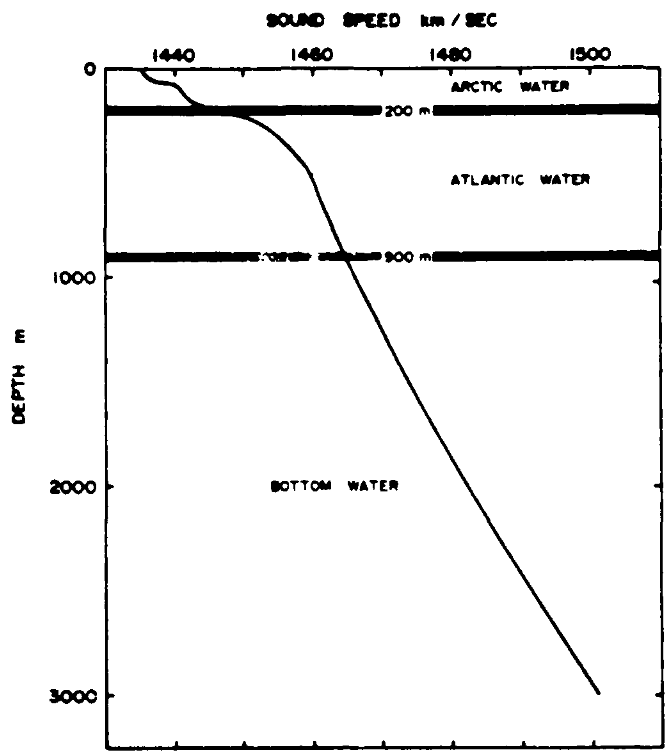

FIGURE 10: TYPICAL SOUND SPEED VERSUS DEPTH FOR THE CANADA DEEP, SHOWING WATER MASSES[30]

The presence of a strong upward refracting sound-speed profile and a rough-ice surface with a distribution of large ridges may lead to significant out-of-plane scattering. The acoustic system impacts of this scattering are twofold. First, significant beam widening may result from the multiple interactions with the randomly rough surface, similar to that observed in shallow water. In addition, the presence of ice ridges in the vicinity of the receiver leads to multiple source images or beam steering errors from the deterministic interaction of the acoustic signal with the face of local ice ridges. Both of these effects may significantly decrease the ability of sonar systems to detect, vector, and localize targets of interest.

The effect of the small-scale roughness of the ice surface might be analogous to the problems encountered in propagating in shallow water situations where rough bottoms are present. The upward refracting Arctic profile results in much of the acoustic energy interacting with the ice canopy every few miles. At each interaction, the roughness of the ice may result in scattering from features of a size comparable to an acoustic wavelength. The resulting signal

30. A.R. Milne, "Sound Propagation and Ambient Noise Under Sea Ice," In Underwater Acoustics, Volume 2, V.M. Albers (editor), Plenum Press, 1967, pp. 103-138.

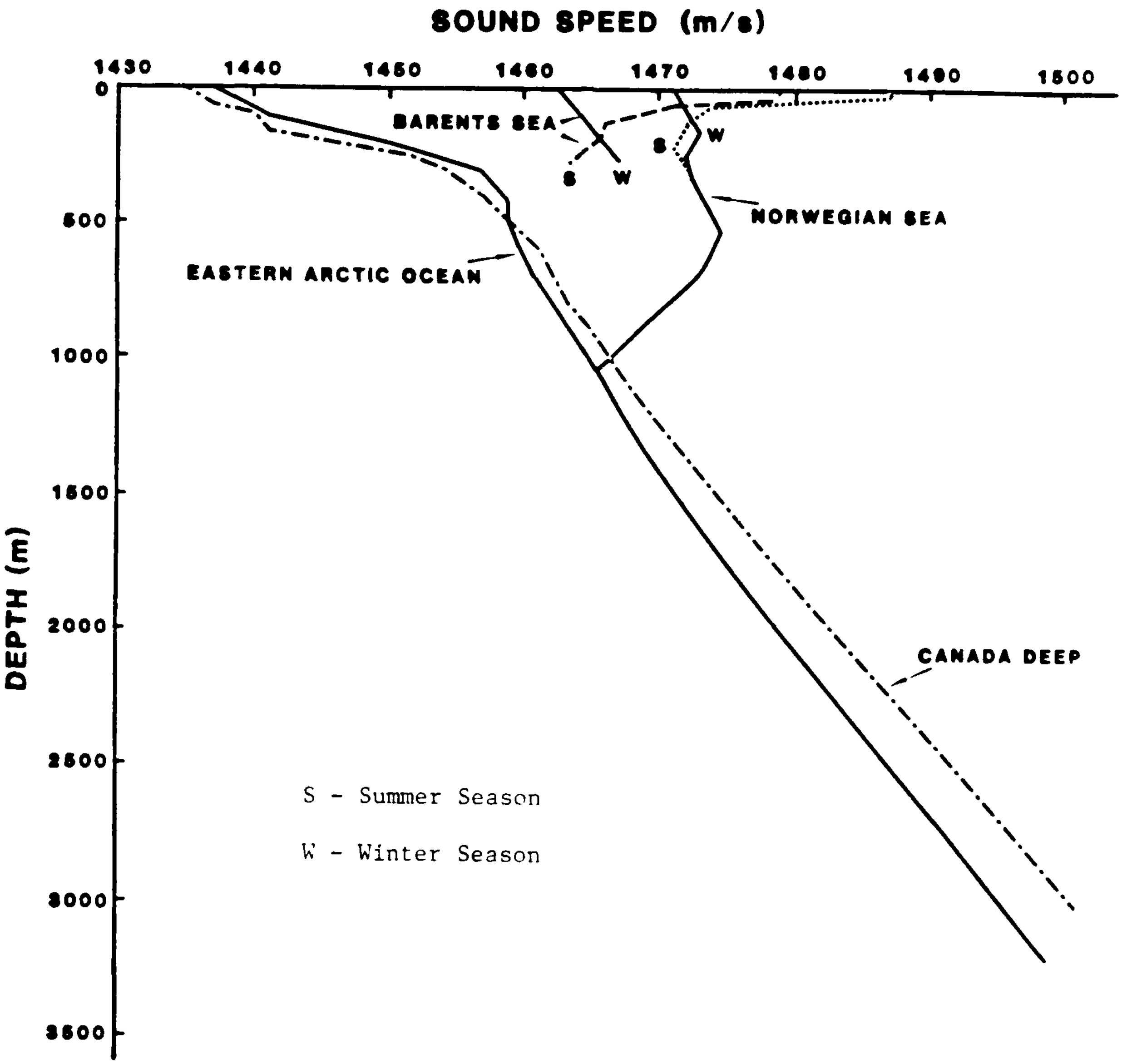

FIGURE 11. COMPARISON OF SOUND SPEED PROFILES FROM THE ARCTIC AND ADJACENT SEAS

will actually arrive from a series of out-of-plane paths that will differ only slightly in phase but will lead to loss of signal coherence. Additional loss of coherence will occur over a wide aperture resulting from the spatial decorrelation of the surface scatterers. Signal levels may be reduced and will be less correlated in space due to the spreading of energy in horizontal angle. Potential for passive detection of this signal will be impacted by the lower energy levels, and the array gain will be limited due to the spread of the received signal. Depending on the magnitude of this effect, significant degradation of array performance may result.

The presence of large ice keels may also lead to large out-of-plane scattering so that signals from multiple directions result in significant deviations from the true bearing. The tilted facets of these keels will result in multiple arrivals with varying horizontal directions, none of which may give a true bearing. The effect of this "glint" will vary with source and receiver location relative to the ice keels so that significant difficulty may be encountered in tracking algorithms. This effect will make localization with active sonars difficult, as well, and the out-of-plane multipath may impact passive ranging techniques.

BOTTOM.[31] The upward refracting nature of the Arctic sound velocity profile in the MIZ and Pack Ice areas will tend to reduce the importance of the interaction with the bottom, except for those systems depending on a bottom interacting propagation path. For such systems, bottom interaction will have an impact similar to that found in other deep water areas. However, in deep Arctic water, the importance of bottom interaction is likely to be negligible for some systems when compared to the effects of the ice cover, either broken or full. The relative importance of these interactions is not yet established. It is possible that bottom interacting systems may have an advantage in ice covered Arctic areas if interaction with ice cover can be avoided. For shallow water areas in the Arctic, the bottom interaction will be important, as it is in all shallow water areas.

The acoustical parameters of the ocean floor and sub-bottom are poorly known for the Arctic. Difficulties in obtaining direct samples (cores) to great depths in the sediment limit the data base available from which to extract quantities needed to determine many of the major acoustical processes used to describe the bottom interaction. Estimates of these geoacoustical parameters from those known for other areas may not be meaningful because the basic processes of sedimentation at work in the Arctic area are unique to that environment. Sedimentation rates are very low, being dominated by material carried by the ice rather than by material of biologic origin as is the case in more temperate areas. The ice pack may also carry large boulders of glacial origin and deposit them in the Arctic Ocean. The low sedimentation rate leaves them exposed as potential scatterers for energy over a wide frequency range.

Detailed information regarding the geochemistry, sedimentology, recent geomorphology and the distribution patterns of sediment types as well as grain size and velocity of sediments are extremely limited for the Arctic. As a result, the specification and identification of the Arctic bottom class provinces (Figure 12) have been qualitatively derived. The derivation of the Arctic bottom

31. Mobile Sonar Technology.

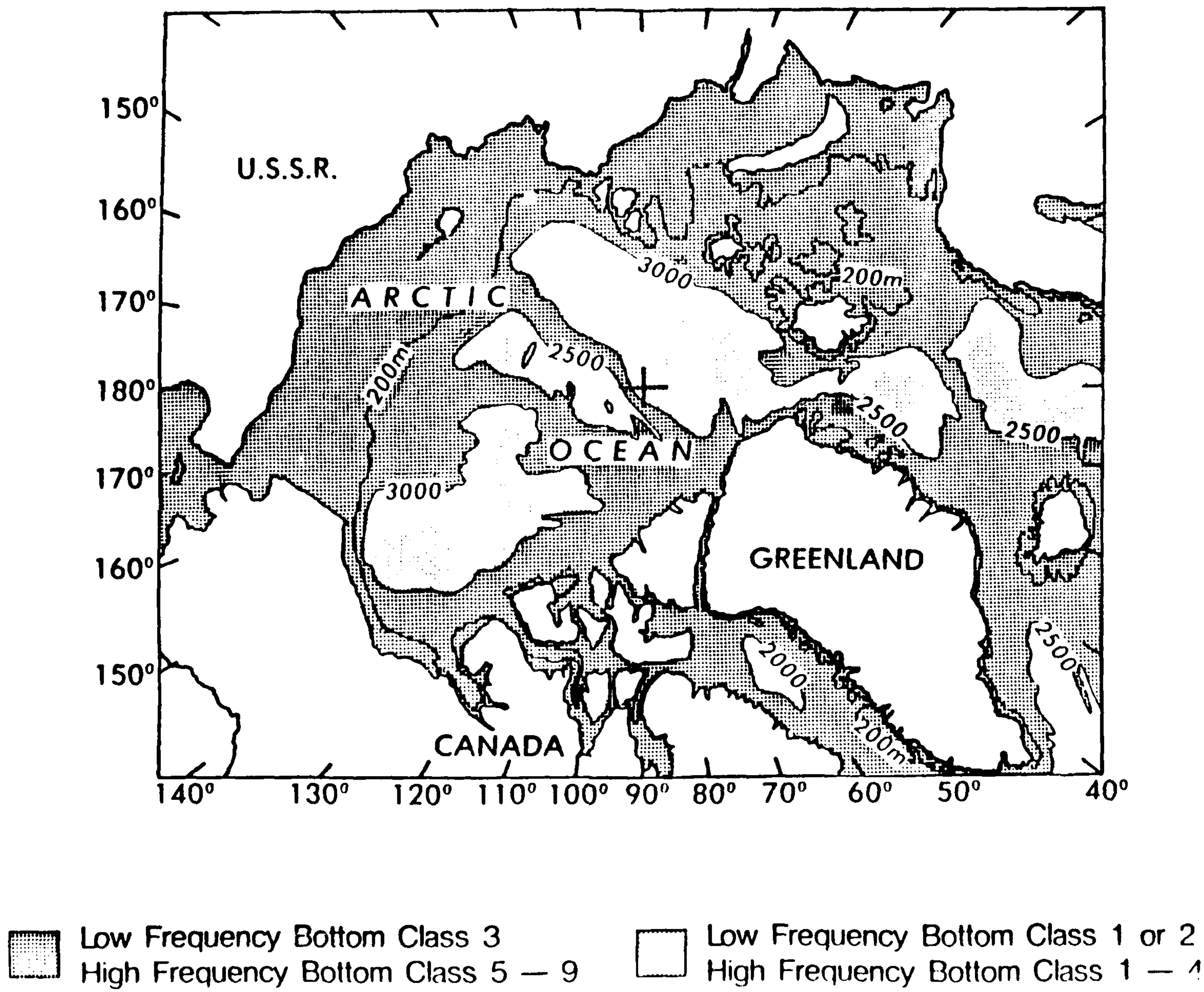

FIGURE 12: ARCTIC BOTTOM LOSS CLASS PROVINCES

classes for low frequency and their respective province boundaries conducted by NORDA principally by extrapolation of the concepts and general ideas employed in IBLUG. The high frequency bottom class provinces were determined principally on the identification of assumed high loss areas.

High loss areas were assumed for regions of ridges, steep shelf and slope, and those being of close proximity to their sediment source (nearer to the source -- the larger, generally, the grain size). Low loss areas were assumed primarily for regions of the deep abyssal plains, regions far from terrigenous sources (rivers), regions of known turbidity current deposition, and the assumption that regions further from their potential sources reflect smaller, finer grain size. Physiographic maps and bathymetric charts were also used to assist, to interpret and to develop Arctic bottom class provinces for both low and high frequencies.

PROPAGATION

Acoustic waveguides in the Arctic are determined by the geometry of the ocean (type of ice cover and depth of bottom) and by the sound speed profile.

The continuously upward-refracting propagation conditions which generally prevail in Arctic waters cause repeated interactions with the ice canopy and tend to act as a low-pass filter (Figure 13). The situation is further complicated when the geometry of the ocean floor and the acoustic wavelength combine to yield shallow-water conditions with the attendant increase in bottom interaction opportunities.

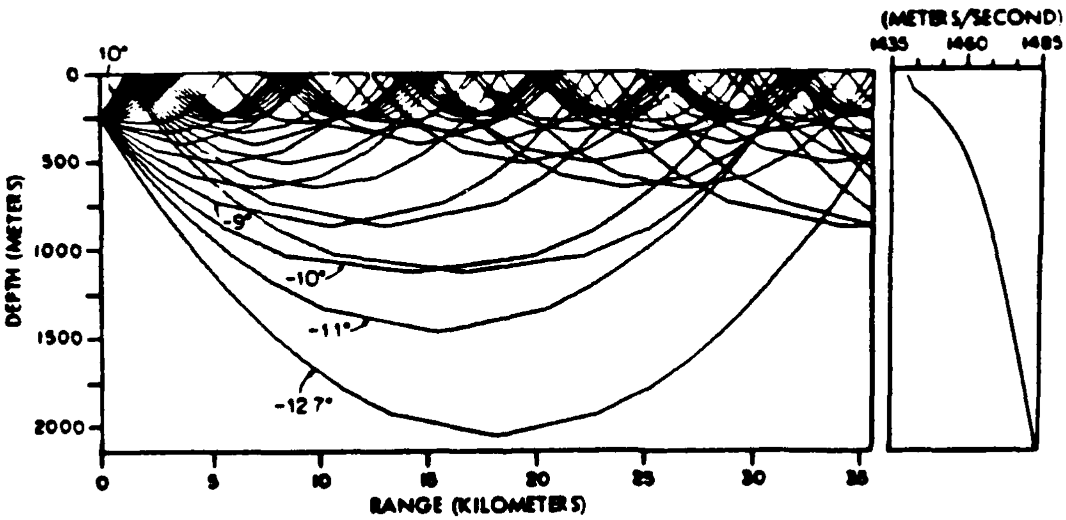

FIGURE 13: TYPICAL SOUND SPEED PROFILE AND CORRESPONDING RAY DIAGRAM FOR SOUND PROPAGATION IN THE ARCTIC OCEAN[32]

32. O.I. Diachok, "Effects of Sea-Ice Ridges on Sound Propagation in the Arctic Ocean," Journal of the Acoustical Society of America, Volume 59, 1976, pp. 1110-1120.

Measurements of propagation loss in the Arctic are limited since access to this region is generally restricted to the spring season; consequently, there is a relatively poor understanding of the seasonal variability.

One of the principal characteristics of acoustic propagation loss measurements under ice cover is a rapid increase of loss with range at frequencies above about 30 Hz. The loss mechanism has been principally attributed to the "scattering" at the ice-water interface. However this is not likely to be the principal mechanism, as it implicitly assumes that the sound is scattered into steep enough vertical angles to be dissipated in the bottom sediment. Other possible dissipative mechanisms are dissipative processes in the ice canopy, conversion of water-borne energy into energy travelling in and confined to the ice canopy, and increased absorption in the water column. A more recent investigation of low-frequency attenuation in the Arctic[33] has utilized a finite impedance scattering formulation which appears to be in good agreement with experimental data.

AMBIENT NOISE[34,35]

The noise environment under ice is different from that of any other ocean regime. Shipping noise is extremely low due to the lack of surface traffic. However, the ice cover affects the ambient noise significantly. It may either shield the water from the forces of the wind to produce a quiet condition which is much quieter than sea state zero, and at other locations and times the ice may produce loud cracking and splashing noises as it is acted on by wind, waves, and thermal effects.

The character of the ice cover is different in areas of shore-fast pack ice, moving pack ice, and the Marginal Ice Zone (MIZ). The underice noise level, directionality, spectrum shape, and temporal character are very different in the above three regions.

SOURCE MECHANISMS.[36] Source mechanisms for ambient noise in the Arctic Ocean are discussed below and summarized in Table 4.

- Ice Stress, Crunching and Bumping

  Ice is subject to current stress, to geographic tilt, to the Coriolis force, to continental shear, and to other forces which can give rise to a particular state of stress in the ice. These imperfections in the ice are potential sites of internal ice transients which tend to relieve the ice stress, and will be excited whenever the ice stress exceeds a

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33. R.H. Mellen, "Arctic Ice Attenuation Model Study," Naval Underwater Systems Center Technical Report 8089, 1987.

34. O.I. Diachok, "Arctic Hydroacoustics," Cold Regions Science and Technology, Volume 2, 1980, pp. 185-201.

35. Milne.

36. Mobile Sonar Technology.

TABLE 4: ARCTIC AMBIENT NOISE MECHANISMS

Mechanism	Environmental Correlates	Spectral Density	Approximate Noisy (Quiet) Spectrum Levels db re 1u Pa @ Hz	Temporal Character	State of Scientific Knowledge	Most Significant Scientific Uncertainties
Large scale ice stress relief	Distance from event; basin scale wind/current stress; closeness to shorefast shear zone	$S \sim \frac{(f/f_o)^2}{1+(f/f_o)^4}$ $f_o \lesssim \frac{1}{2}$ Hz	at f_o: $\gtrsim 130$ when within 1 km of event	Episodic: - each episode 0 (10 days) - repeat period 0 (10 days) - 20 to 400 events per day in episode	Poor	S, f_o, episodic character threshold stress
Mesoscale ice stress relief	Mesoscale wind/current stress	$S \approx \frac{(f/f_o)^2}{1+(f/f_o)^4}$ $f_o \approx 15$ Hz	at f_o: 90 (65)	Slowly varying with atmospheric time scales (e^{-1} times: ~ 2 to 6 hr)	Fair	Threshold stress, distribution on scale of individual events
Small scale ice stress relief	Temperature gradients in ice; snow cover insulation; brittleness of ice	$S \approx \frac{(f/f_o)^2}{1+(f/f_o)^4}$ $f_o \approx 300$ Hz	at f_o: 80 (50)	Diurnal variation with atmospheric cooling	Fair	Threshold stress, distribution on scale of individual events
Ice crunching (ridge building)	Distance from ridge; closeness to shorefast shear zone	Unknown	$\gtrsim 130$ when within 1 km of event	Sporadic	Poor	Spectrum, ice stress conditions
Ice bumping	Ice concentration; mean floe size; wind current, Coriolis stress	Unknown	Unknown	Unknown	Poor	Importance of effect
Water/ice interaction	Distance from ice edge; wave period T; ice concentration C; wind direction	$100 \lesssim f_o \lesssim 1000$ Hz $S \sim \frac{(T/To)^4}{(f/f_o)^2}$ $f < 100$ Hz: Unknown	F = 100 Hz; T = 10 sec; c = 1: 87 c $\lesssim$ 7/8: 77	Slowly varying with wave and wind conditions	Poor	Low frequency spectrum mechanism (splashing cracking or other)
Snow Pelting	10 m wind speed V; snow grain availability	$V \leq 8$ kts: $S \sim 0$ $V > 8$ kts: $S \sim \left(\frac{V}{Vo}\right)^3 \frac{(f/f_o)^7}{1+(f/f_o)^{12}}$ $f_o \sim \frac{V}{2}$ kHZ	at f_o: 55 at 10 kts	Slowly varying with atmospheric time scales (e^{-1} times: 2 to 6 hr); sporadic with gusts.	Fair	Available snow pelting model doesn't predict observed spectrum
Micro earthquakes (T phase)	Distance from epicenter; magnitude M	$S \approx \left(\frac{M}{M_o}\right)^2 \frac{(f/f_o)^3}{1+(f/f_o)^3}$ f_o 20Hz	at f_o: > 85 (unknown M)	Sporadic: 10 dB down event length ~ $\frac{1}{2}$ min. Number of events per year $\sim 10^{5.17-0.91M}$ (not uniformly distributed)	Poor	Quantitative connection of peak spectral level with M, clustering of events
Biological Sounds	Distance from herd or school	Various	Various	Sporadic	Poor	Source level of individuals, herding or schooling habits

*Derived from I. Dyer (M.I.T.) submission to NRL Arctic Planning Group (December 1982).

threshold for such motion. Spectral components with peak frequencies on the order of 1/2 Hz or less, 15 Hz or so, and 300 Hz or so are almost always observed when ice stress is present.

In contrast to ice stress, crunching is an event localized in time and space. Noise associated with the collision of ice floes and the subsequent building of a pressure ridge may only be a chaotic superposition of ice stress relief noises of varying scales. Individual floes of ice can collide, causing transient waves to propagate in the ice, and thus generate noise in the water. Such bumping noises are most apt to occur at intermediate ice concentrations, since for either low or very high concentration the probability of collision is low.

- <u>Wind-Wave-Ice Interactions</u>

  Ambient noise levels measured near the ice edge are observed to be high and may be related to the disparate sizes of ice floes and wavelengths of incoming swell. Disparity can cause the ice to crack or to act as a barrier against which waves might splash.

  Wind stresses applied to ice are immediately manifested as changes in ambient noise level. Changes of up to 20 dB across the frequency regime from 20 Hz to 1 kHz have been measured as a function of wind speed.

  At sufficiently high speed, it has been shown that frozen snow pellets can be lifted from the surface of the ice and fall back upon it. Observations both in shorefast regions and in the central Arctic show that such snow pelting noise can be dominant at frequencies on the order of 10 kHz, but less likely to be important at frequencies below 1 kHz. Also, such noise does depend upon exceeding a threshold of wind speed, which for typical snow pellets during winter is on the order of 8 knots. Snow pelting noise is not likely during the summer season in which the ice is covered with melt pools or wet snow.

- <u>Seismic Activity</u>

  The Lomonosov Ridge is tectonically active and emits earthquake noises. Such noises can be detected in the water column for distances in excess of several hundred kilometers from the ridge, depending upon earthquake magnitude. While micro-earthquake noise is rarely dominant in the Arctic, when averaging over several minutes or more, it can significantly increase the ambient noise level over tens of seconds. Each of the primary, secondary, and tertiary phases of earthquake signals have been observed. Of most interest is the tertiary phase since it lasts the longest and carries the most acoustic energy. This has been determined to be due to scattering mechanisms in the water column above the earthquake epicenter, and depends upon the ice and bottom roughness over the epicenter.

- Biologic Activity

  Some regions and some seasons of the Arctic Ocean support a biological chain which includes fish and mammals. Sounds associated with such animals are typically localized in both space and time and may be both broadband and narrowband in character. Generally such noises are not dominant, but when they are, they can usually be identified as sounds peculiar to given forms of life. (Also, see Section II for related discussions.)

SPECTRAL LEVELS AND SPATIAL DEPENDENCIES.[37,38] The Arctic ambient noise spectrum has been synthesized according to the source mechanisms identified in Table 4. Excluded from this table and from other consideration in this summary are noise sources typically met and reasonably understood in the open oceans. These include wind-generated noise, distant-shipping noise, and molecular agitation. At low frequencies, there is reason to believe that open-ocean mechanisms such as distant-shipping noise can propagate well under the ice, but no specific estimates of this factor have been made.

Even in pack-ice areas, ice is very dynamic and highly variable in space and time. Most of the mechanisms described above are sources of noise in the pack-ice regions. Under the pack-ice cover, however, the lack of wind-wave interaction and the absence of local shipping can lead to noise levels 10 dB below those encountered in the open ocean.

Noise levels in the MIZ are typically higher than those in either the pack-ice regions or the open ocean regions. Figure 14 illustrates the variations in median ambient noise level that occur across a compact ice/water MIZ zone. Ambient noise levels in the MIZ also depend on such variables as sea state, water depth, and dominant ocean-wave period. The latter variable is hypothesized as being related to the efficiency of coupling of ocean-wave energy into the ice.

In the low S/N (Signal to Noise) ratio situation typical of initial detection situations, a driving factor for detection range is the ambient noise. Arctic ambient noise can be highly directional, in both the horizontal and the vertical planes. Hence, array gains better than the DI (Directivity Index) may be possible. In particular, rejection of local, high-vertical-angle noise sources or localized distant noise sources at various azimuths may exceed the potential for rejection of isotropic noise.

REVERBERATION

The detection, localization, and classification with active sonars of targets hovering close to the ice canopy is limited primarily by both reverberation from the rough under-ice surface and false targets from large ice features such as keels. In contrast with Arctic seas, wave motion in ice-free seas adds to the sound speeds of signals reflected from them. Thus, sea wave motion produces Doppler frequency broadening of reverberation signals that can mask Doppler

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37. Mobile Sonar Technology.

38. Diachok, Cold Regions Science and Technology.

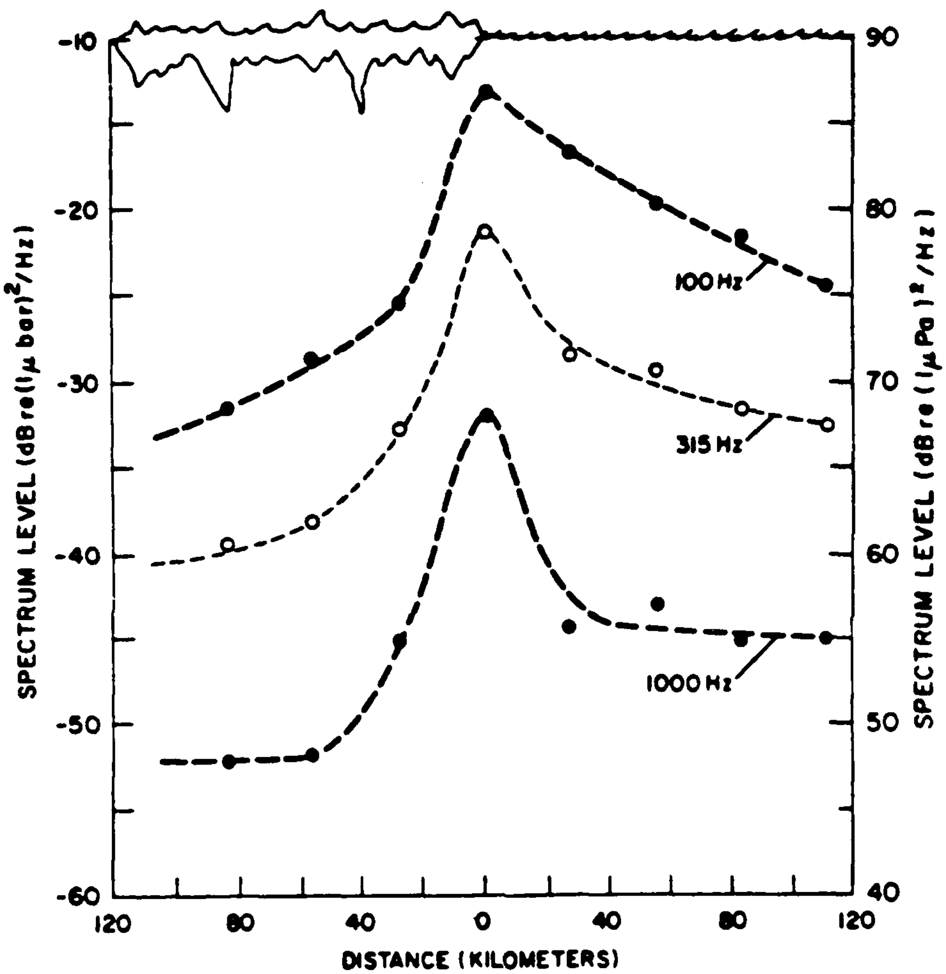

FIGURE 14: VARIATION OF MEDIAN AMBIENT NOISE SOUND PRESSURE SPECTRUM LEVELS WITH DISTANCE FROM A COMPACT ICE EDGE FOR FREQUENCIES OF 100, 315, AND 1,000 Hz; SEA STATE 2[39]

39. Diachok, Cold Regions Science and Technology.

frequency shifts of targets in motion. Under sea ice, however, such frequency shifts of echoes from moving targets could possibly be observed within the higher reverberation noise.

Reverberation is a time-dependent noise occurring in a sound receiver shortly after the emission of an outgoing signal from an underwater projector. It is the sum of all the false signals scattered back from the volume and the boundaries of the sea. Sea ice is the dominant cause of reverberation noise in Arctic regions. For undeformed first-year ice, the reverberation noise for frequencies above 3 kHz is about equivalent to that expected from an ice-free sea surface with a 30-knot wind blowing. In broken pack ice in the springtime this noise can increase by 20 dB.[40]

Reverberation in the Arctic is a serious problem. It is so serious that little consideration is given to active sensors. Torpedoes, which use active homing, have had difficulties in the past because of so called "ice capture," which is a direct result of the reverberation. A target with dimensions of the order of the mean amplitude of the underice irregularities may be completely buried in the reverberation noise at all ranges.

Volume reverberation in the Arctic is not appreciable due to a decreased scattering layer concentration compared to the open ocean. The scattering layer, which is believed to be caused by marine life, has been found to exist in the Arctic at depths of 160 to 650 ft, which is considerable more shallow than the open ocean. The scattering layer exhibits an annual rather than a diurnal cycle like the open ocean. The layer occurs at moderate depths due to the weak light levels under the ice, and is present in the summer when sunlight prevails. In the winter, when it is dark, the organisms are near the surface and the layer disappears. The layer sometimes splits into two or three parts, just as it does in the open ocean. Volume reverberation due to the scattering layer is low compared to the 40 dB re $(1\mu Pa)^2/Hz$ level usually observed in the open ocean and is quite insignificant compared to ice scattering.

Because of the variation int the underice surface, the scattering strength measurements as a function of grazing angle, taken by different observers, demonstrate different characteristics. When the underice surface is relatively smooth, the scattering strength increases with grazing angle as in the open ocean. When ridge keels are present, the low grazing angle sound wave strikes these in a near-normal incidence and high reflections occur. Then as the angle becomes greater, less reflection takes place. Figure 15 shows the results of measurements from the backscattering strength of the ice-covered sea for two Arctic locations at different times of year. Included in Figure 15 are curves of the backscattering of the ice-free sea at a 25-knot wind speed. Both sets of data for underice scattering show an increase of scattering strength with frequency and grazing angle. The analyst, accordingly, has only fragmentary data available on which to base a prediction of the reverberation to be expected under an ice cover, although it is clear that backscattering strengths higher than those for the ice-free sea at low and moderate wind speeds must prevail.

40. Welsh, et al.

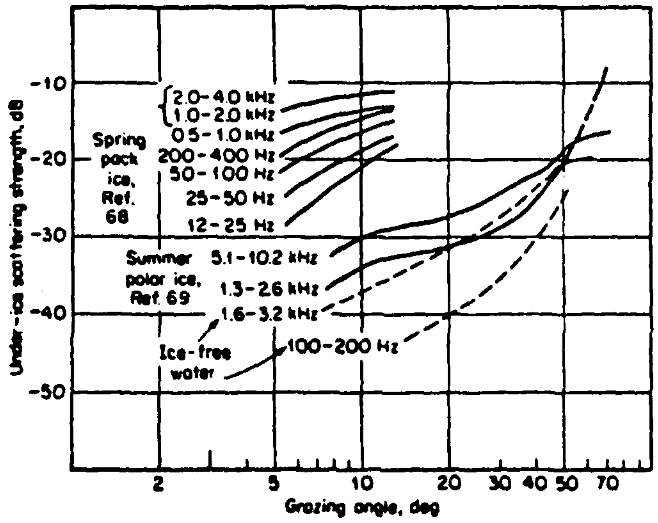

FIGURE 15: SCATTERING STRENGTHS OF AN ICE COVER[41]

Reverberation noise can be minimized by using highly directional sources and receivers to exploit optimum ray paths. Such paths could provide time discrimination between echoes and reverberations for targets spatially separated from the ice surface.

41. R.J. Urick, Principles of Underwater Sound, McGraw-Hill, 1983, 423 pp.

SECTION IV

ARCTIC ACOUSTIC MODELS

ENVIRONMENTAL MODELS

Basic descriptors of the Arctic marine environment which require specialized algorithms are limited to surface (under-ice) scattering and absorption. The generation of other parameters, such as sound speed and bottom scattering, appear to be well supported by existing algorithms valid over wide ocean areas.

A review and evaluation of under-ice scattering loss models[42] resulted in the recommendation of a set of formulas deemed appropriate for use in Arctic propagation loss models. These formulas have recently been incorporated, for example in the RAYMODE passive propagation loss model.[43] The specific recommended algorithms are identified in Table 5.

Absorption is regionally dependent, due mainly to the pH-dependence of the boric acid relaxation. In the Arctic, the pH range is roughly 8.0 - 8.3 (vs. 7.7 - 8.3 for nominal sea water), but the greatest variability occurs much closer to the sea surface than in other ocean areas.[44] Simplified absorption formulas for different ocean areas are presented in Table 6.

PROPAGATION LOSS MODELS

Developments in Arctic Ocean acoustic propagation modeling have been very limited. Much of the past effort on characterizing propagation in the Arctic has been devoted to obtaining acoustical data and developing empirical models based on that data. While these models tend to be site (and season) specific with little generality, they do provide basic information on frequency and range dependence of propagation.

In general, there are four factors peculiar to the Arctic environment which complicate the modeling of acoustic propagation in the region: 1) the ice keels present a rapidly varying surface, 2) the reflection, transmission, and scattering properties at the ice interface are not well known, 3) the measurement of underice contours is difficult, and 4) the diffraction around ice obstacles may be important. However, in the Arctic surface duct, ray theory may provide a useful

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42. A.I. Eller, "Findings and Recommendations of the Under-Ice Scattering Loss Model Working Group," Naval Ocean R&D Activity Technical Note 255, 1985, 29 pp.

43. P.D. Hill, "A Proposed Interim Standard Ice Scattering Model. Validation and Analysis," Naval Underwater Systems Center Technical Memorandum No. 86-2020, 1986.

44. R.H. Mellen, P.M. Scheifele and D.G. Browning, "Global Model for Sound Absorption in Sea Water. Part III: Arctic Regions," Naval Underwater Systems Center Technical Report 7969, 1987.

TABLE 5: RECOMMENDED ALGORITHM FOR UNDER-ICE SCATTERING LOSS[45]

Scattering loss in dB per bounce is given by Loss = -10 log R where R is the greatest of

$$R_1 = 1 - \pi^2 N k^3 d^2 \left(\frac{d+w}{2}\right)^2 \sin\theta$$

$$R_2 = 1 - 4 \sin\theta \, k^2 \sigma^2 \left(1 - \pi^2 c \sin\frac{\theta}{2}\right)$$

$$R_3 = 1 - 4.79 \sin\theta \; c(k/\beta)^{1.5}$$

$$R_4 = \begin{cases} \dfrac{(\sin\theta - X)^2 + X^2}{(\sin\theta + X)^2 + X^2}, & X < \sin\theta \\ 0.2, & X > \sin\theta \end{cases}$$

where $X = 1.311 \; c(k/\beta)^{1/2}$

N	=	linear density of ridges (number of ridges per unit distance); typical value: N = 10/km
d	=	keel depth } typical value: w/d=1.6
2w	=	keel width }
Θ	=	grazing angle
σ	=	rms ice roughness
c	=	$N\pi d^2/8w$
β	=	$(2c)^{1/2}/\sigma$
k	=	acoustic wave number

$$R_5 = \left|\frac{1+Z}{1-Z}\right|^2 ,$$

$$\text{where } Z = -\frac{NL}{\cos\phi}\left[\cos(\phi-\gamma) + \frac{\tan\phi \sin(2kL\sin\gamma\cos\phi)}{2kL}\right]$$

$$L = d\left(\frac{1+\rho^4\cot^2\phi}{1+\rho^2\cot^2\phi}\right)^{1/2} , \quad \rho = w/d$$

$$\tan\gamma = \rho^{-2}\tan\phi , \quad \phi = \frac{\pi}{2} - \theta .$$

In all cases the maximum loss is 7 dB.

45. Eller.

TABLE 6: SIMPLIFIED ABSORPTION FORMULAS[46]

$$A = A_1(MgSO_4) + A_2(B(OH)_3) + A_3(MgCO_3)$$

$$A_n = (S/35)\, a_n f^2 f_n / (f^2 + f_n^2)$$

$$a_1 = 0.5 \times 10^{-D(km)/20} \qquad f_1 = 50 \times 10^{T/60}$$

$$a_2 = 0.1 \times 10^{(pH-8)} \qquad f_2 = 0.9 \times 10^{T/70}$$

$$a_3 = 0.03 \times 10^{(pH-8)} \qquad f_3 = 4.5 \times 10^{T/30}$$

Atlantic 4°C pH 8.0 $A = 0.007f^2 + 0.1f^2/(1+f^2) + 0.18f^2/(6^2+f^2)$
N.Pacific 4°C pH 7.7 $A = 0.007f^2 + 0.05f^2/(1+f^2) + 0.09f^2/(6^2+f^2)$
Mediterranean 14°C pH 8.3 $A = 0.006f^2 + 0.26f^2/(1.4^2+f^2) + 0.78f^2/(12^2+f^2)$
Red Sea 22°C pH 8.2 $A = 0.004f^2 + 0.27f^2/(1.8^2+f^2) + 1.1f^2/(24^2+f^2)$
sub-Arctic -1°C pH 8.3 $A = 0.01f^2 + 0.17f^2/(0.85^2+f^2) + 0.24f^2/(4^2+f^2)$

A	:	(dB/km)	:	absorption
f,fn	:	(kHz)	:	frequency, relaxation frequencies
T	:	(°C)	:	temperature
pH	:	(8.0)	:	reference value

predictive method, whereas its utility in temperate water surface ducts may actually be quite limited. The utility of ray theory in the Arctic derives from the fact that the Arctic surface half-duct is between one and two orders of magnitude greater in gradient and depth than the temperate water counterpart. The strong positive thermocline and halocline produce an exceptionally strong positive sound speed gradient in the subsurface layer. This markedly shortens the ray loop length causing many surface reflections for rays with small grazing angles.[47]

46. Mellen, et al., NUSC TR 7969.

47. Mobile Sonar Technology.

The open ocean region in the Arctic environment also poses potential problems as far as present propagation models are concerned. Surface reflection-losses, which are generally not significant, become more important because multiple surface reflections play a dominant role. Moreover, multiple ducts are prevalent in this region and are not adequately treated by many propagation models.

Two basic modeling approaches are currently being pursued: 1) application of ice-scattering coefficients to existing numerical models of acoustic propagation loss, and 2) development of semi-empirical models. These two approaches are discussed in more detail below.

NUMERICAL MODELS. Numerical models of underwater acoustic propagation loss specifically designed for ice-covered regions are limited. In fact, only three such models are known to exist: Kutschale Fast Field Program (FFP),[48] Multiple Scattering Pulse FFP (MSPFFP)[49] and Fast Normal Mode with Surface Scattering Integrals (FNMSS)[50]. These models are considered most appropriate for prediction of low-frequency transmission loss (<350 Hz) at long ranges (>25 nm). Several other existing models might be suitable for calculation of mean transmission losses if the needed descriptions of the ice cover were available; a recent survey has identified more than forty such models.[51] For example, numerical values of under-ice reflection loss as a function of grazing angle have been incorporated into the RAYMODE[52] and TRIMAIN[53] models. However, it should be noted that all numerical models, regardless of theoretical basis, are inherently limited by the approximations required to achieve a tractable solution.

48. H.W. Kutschale, "Rapid Computation by Wave Theory of Propagation Loss in the Arctic Ocean," Lamont-Doherty Geological Observatory Report CU-8-73, 1973.

49. H.W. Kutschale, "Arctic Marine Acoustics," Final Report under Contract No. N00014-80-C-0021, Lamont-Doherty Geological Observatory of Columbia University, Palisades, NY, 1984.

50. D.F. Gordon and H.P. Bucker, "Arctic Acoustic Propagation Model with Ice Scattering," Naval Ocean Systems Center Technical Report 985, 1984.

51. P.C. Etter, R.M. Deffenbaugh and R.S. Flum, Sr., "A Survey of Underwater Acoustic Models and Environmental-Acoustic Data Banks," ASW Systems Program Office Report ASWR-84-001, 1984.

52. Hill.

53. R.L. Deavenport and F.R. DiNapoli, "Evaluation of Arctic Transmission Loss Models," Naval Underwater Systems Center Technical Memorandum No. 82-1160, 1982.

The three dedicated Arctic propagation loss models are now described in more detail.

- <u>Kutschale FFP</u>

  This model, developed by H. Kutschale at Lamont-Doherty Geological Observatory, is a rapid, accurate method of computing propagation loss as a function of range in the ice-covered Arctic Ocean. Input parameters to the propagation model are source and detector depth, wave frequency, ice roughness, bottom topography, and the velocity structure as a function of depth in the ice, water, and bottom. Computation is done by direct integration of the exact integral solution of the wave equation derived from a harmonic point source located in a multilayered, interbedded liquid-solid half space. The integration technique introduced by H.W. Marsh, employs the Fast Fourier Transform for very rapid evaluation of the integral solution. Computed propagation loss as a function of range is in good agreement with field data.

- <u>MSPFFP</u>

  This model, also developed by H. Kutschale, decomposes the Fast Field Program into ray path type contributions. Each decomposed term can be interpreted as the desired path contribution for a corresponding bottom-interacting pulse. The Fast Field Program (FFP) algorithm integrates directly the full wave solution. Thus, the MSPFFP technique is a natural scheme with which to model the bottom-interacting pulses, which correspond to the coherent summation of many modes over a limited time interval. Temporal waveforms are computed by Fourier synthesis.

- <u>FNMSS</u>

  This program determines modes for perfectly reflecting boundaries. Mode attenuation is then computed from boundary loss tables. Forward scattering at the surface is computed for all ray paths from the source to the surface and from the surface to the receivers for each mode. Modes can be added coherently or incoherently and the scattering is added incoherently. Losses for the 10 and 90 percentile points of the scattering contribution assuming a Rayleigh distribution are optional outputs. Surface losses can be specified as linear functions of grazing angle, as wind speeds or wave heights for open ocean surfaces, or as multiples of "normal" pack ice scattering for the Central Arctic. The use of real modes computed for ideal boundaries with boundary loss added later permits rapid mode computation. This technique is slightly inaccurate at frequencies where a very few modes are trapped in a duct, but gives excellent accuracy at higher frequencies. Some modes may be omitted in multiple duct profiles, but all modes in the duct containing the source will be computed.

As mentioned earlier, there are other existing models which can be adapted for use in the Arctic through the inclusion of under-ice scattering algorithms. Specifically, the RAYMODE model appears to be particularly attractive in this regard since it has already been modified,[54] and has the benefit of some real-world applications.

SEMI-EMPIRICAL MODELS. Semi-empirical models are inherently limited by the data bases from which they were derived. Attempts to fit results from a large data set with simplistic curves generally implies large errors in the model results. Comparisons of model results with data are clearly quite limited by a lack of comprehensive data sets.

Two of the better known semi-empirical models are described below.

- Marsh-Mellen Arctic Transmission Loss Model[55,56] is based on observations made during the summers of 1958 and 1959 between Arctic drift stations separated by 800-1,200 km. The measured arrivals were found to consist of a dispersive, quasi-sinusoidal wave train in the 10-100 Hz frequency range; these features were explained by a half-sound channel model in which the higher frequencies were attenuated by under-ice scattering. Using these and other experimental data, long-range, low-frequency (<400 Hz) transmission loss in the Arctic were fit with an equation of the form:

$$TL = 10 \log r_o + 10 \log R + \alpha_s N_s$$

where: r_o = skip distance for limiting ray that is turned at a depth of approximately 350 m

N_s = number of surface reflections

R = range in m ($R = r_o N_s$)

α_s = loss per bounce

- Buck Arctic Transmission Loss Model[57] consists of a short-range (10-100 nm) and a long-range (100-1,000 nm) model for low-frequency transmission loss in that part of the Arctic Ocean deeper than 1,000 m. These empirical models represent linear regression fits to winter data from the Beaufort Sea (1970) and the Fram Strait (1977, 1979):

$$TL \text{ (short range)} = 62.4 + 10 \log R + 0.032 f + 0.065 R + 0.0011 fR$$

54. Hill.

55. H.W. Marsh, "Sound Reflection and Scattering from the Sea Surface," Journal of the Acoustical Society of America, Volume 35, 1963, p. 240.

56. Deavenport and DiNapoli.

57. B.M. Buck, "Preliminary Underice Propagation Models Based on Synoptic Ice Roughness," Polar Research Laboratory, Inc. Report No. PRL TR-30, 1981.

$$\text{TL (long range)} = 68.5 + 10 \log R + 0.07 f - 0.0015 sR + 0.000487 fsR$$

where: f = frequency in Hz

R = range in nm

s = standard deviation ice depth

NOISE MODELS

No Arctic-specific underwater acoustic noise models are known to exist. Even existing numerical models of ambient noise cannot readily be adapted to the Arctic environment since the two primary noise sources modeled (wind/wave action and shipping traffic) have no meaning in the traditional sense. Thus, it has been common practice to assume Sea State 'zero' condition, with little or no shipping, in order to approximate under-ice noise levels. Near the ice edge, and in the MIZ, noise levels increase over those of even adjacent open-ocean areas. However, levels some 40 dB higher have been observed when the ice had been actively cracking under falling air temperatures.[58]

REVERBERATION MODELS

Measurements of under-ice reverberation reveal that reverberation levels can increase by as much as 40 dB over ice-free ocean areas.[59] This increase is due to the large - and small-scale surface roughness of the under-ice surface, the properties of which are only poorly understood.

Two reverberation models which treat the Arctic environment directly are available, as described below.

- Under-Ice Reverberation Simulation[60]

  This model has been developed to evaluate reverberation produced by the backscatter of a high-frequency acoustic pulse from pack ice regions characteristic of the interior Arctic. The model uses measured two-dimensional under-ice acoustic profile data and several empirical results that relate geometric parameters of the large-scale under-ice relief features (e.g., ice keels) to construct a three-dimensional bimodal under-ice surface consisting of first-year ice keels and sloping flat ice regions. A first-year keel is modeled as an ensemble of randomly oriented ice blocks on a planar surface inclined at some slope angle with respect to a horizontal plane at sea level. The keel is characterized by length, draft, width, ice thickness, and

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58. Urick.

59. G.C. Bishop, L.E. Mellberg and W.T. Ellison, "A Simulation Model for High-Frequency, Under-Ice Reverberation," Naval Underwater Systems Center Technical Report 6268, 1986.

60. ibid.

aspect angle. A region of flat ice is modeled as a smooth planar surface whose slope angle is less than some critical angle that serves to distinguish a flat ice feature from an ice keel. The Kirchhoff approximation is used to evaluate the target strength of a facet of an ice block. The target strength of a keel is calculated in range increments as the coherent sum of the backscatter from all scattering facets contained within one-half the pulse length projected onto the keel. The model has been used to show the effects of various ice and acoustic parameters on reverberation and target strength frequency distributions.

- REVMOD - Reverberation Spectrum Model[61]

  The existing REVMOD model has been modified for application to the Doppler sonar problem, where reverberation is both a signal of interest as well as a potential contaminant. Specifically, an adaptive least-squares lattice algorithm is applied to the rejection of under-ice acoustic reverberation.

61. W.S. Hodgkiss, Jr. and D. Alexandrou, "Under-Ice Reverberation Rejection," IEEE Journal of Oceanic Engineering, Volume 10, Number 3, 1985, pp. 285-289.

SECTION V

ARCTIC ACOUSTIC DATA

The most comprehensive assemblage of Arctic environmental acoustic data tailored to support of numerical sonar performance modeling is the Naval Arctic Environmental Acoustic Data Base maintained by the Naval Ocean R&D Activity (NORDA).[62] Table 7 summarizes the parameters presently contained in this data base.

TABLE 7: NORDA ARCTIC DATA BASE CONTENTS

Sound Speed Profiles
Bottom Loss (Low Frequency)
Temperature
Salinity
Bathymetry
Ice Parameters

62. G. Kerr, "A Brief Description of the Naval Arctic Environmental Acoustic Data Base Version 1.0," Naval Ocean R&D Activity Technical Note 322, 1986.

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